A NEW SYSTEM OF PRECISION
VOLTAGE REGULATION

By

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PREFACE

The increasing demand for instruments with a high degree of sensitivity has brought about the need for the development of direct-current power sources with extreme stability. Although much progress has been made toward developing highly stable voltage sources, the advent of new components has made possible improved techniques and circuits for voltage regulation. Two such components are vital to the voltage regulator described in this thesis.

ACKNOWLEDGEMENT

The author wishes to express his sincere appreciation for the encouragement and careful supervision given him by Professor David L. Johnson, his faculty adviser.

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CHAPTER I

INTRODUCTION

Voltage-regulated power supplies are necessary for reliable operation of many electronic devices, including oscilloscopes, vacuum-tube voltmeters, signal generators and other test equipment. The typical commercially built precision power supplies are rated with a regulation of around one half of one percent.[1-4] For example if the output of the source is 300 volts, the variation may approximate one or two volts. Though this regulation may be entirely satisfactory for most applications, there is some equipment whose performance is limited solely by the stability of its power supply. There are also new designs of complex precision electronic apparatus that might be made successful if power-supply stability could be improved.[5]

Although much progress has been made in the field of developing precision d-c voltage supplies, the erratic operation and complexities of certain components commonly used in voltage-regulators make it impossible to obtain stability of as high degree as some electronic equipment demands for sensitive operation.

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1 Chatham Electronics, "Chatham Model EA-50A," Bulletin, (June, 1950).

2 Oregon Electronics, "Regulated Power Supply Models A3 and A3A," Bulletin 52, (June, 1950).

3 Hewlett-Packard Company, "High Regulated Power Supply Model 712A," Bulletin 2057, (June, 1950).

4 Oregon Electronics, "Power Supply Model D6," Bulletin 53, (July, 1950).

5 W. L. Kinsell, "Regulated D. C. Supply Improvements," Radio News, XXXIX (June, 1948), 68-69.

The purpose of the research discussed in this thesis is to present a new method of utilizing recently developed circuit components in performing the actions of a degenerative d-c voltage regulator whose stability is comparable to that of the standard cell.

In order to show clearly the advantages of obtaining regulation by the new system presented in this thesis, the individual components commonly used in d-c voltage regulators were thoroughly investigated and their characteristics compared with the new type components used in this system. To show further that the new system of voltage regulation has definite advantages, operating characteristics of an experimental model have been obtained and recorded.

CHAPTER II

THEORY OF CIRCUITS AND COMPONENTS

The theory of operation of a voltage regulator may best be explained by starting with the basic concepts of the component parts of the different types of circuits.

The action of a voltage regulator circuit is to cancel any attempted fluctuation of its output whether this fluctuation is due to a change in input voltage or a variation in load.[1] Regulators may be classified as "simple" or "degenerative." Degenerative regulators depend on a negative feedback loop to provide power at low impedance and simple regulators merely combine nonlinear elements to effect a low output impedance.[2]

A thorough investigation of technical literature reveals that the majority of the commercially built precision power supplies have the degenerative type of regulation. Because the type of power supply investigated and presented in this thesis is of the degenerative class, the components of the different degenerative types will be discussed in detail.

Figure 1 shows a way in which basic elements of a degenerative regulator may be arranged for explanatory purposes. Block A represents a sampling circuit yielding some desired function of the regulator output.

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1 Paul Koontz and Earle Delatush, "Voltage Regulated Power Supplies," Electronics, XX (July, 1947), 119.

2 Ivan A. Greenwood, J. Vance Holdam and Duncan Macrae, Electronic Instruments, p. 493.

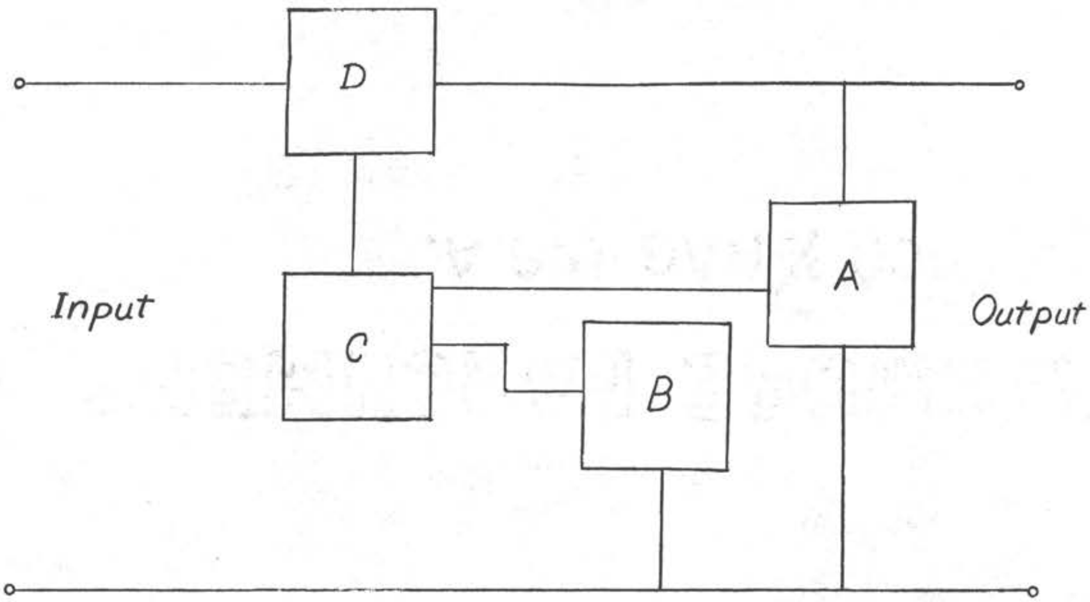

Figure 1

Block Diagram of a Degenerative
D-c Voltage Regulator

A reference element is represented by block B which may be a voltage source, a current source, or an electrochemical device.[3] C represents a comparison circuit which provides an error signal representing the deviation of the output from the output desired. The control element is represented by block D. The divisions in the block diagram represent elements that perform single functions. However, in some regulators the same element may accomplish two or more of the basic functions.

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3 Ibid.

Figure 2 shows the components of a representative degenerative regulator circuit. Since most degenerative regulator circuits are

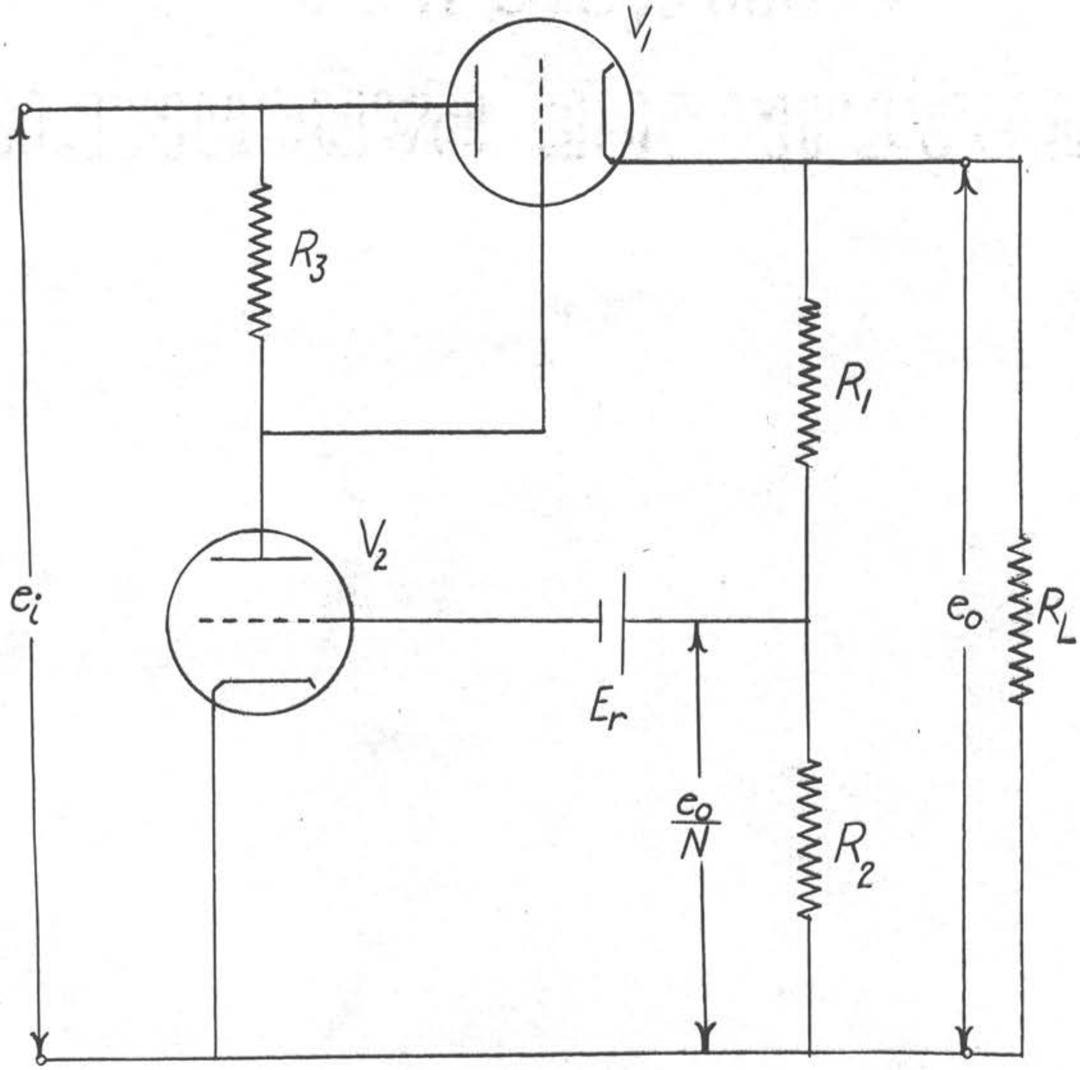

Figure 2

Typical Degenerative Regulator Circuit

similar to that shown in Figure 2, it will be used for a general analysis of degenerative regulators.

For calculation of the performance characteristics of the representative regulator circuit, the following symbols are used. The input and output voltages are e_i and e_o, respectively. Rp_1 and μ_1 refer to the dynamic resistance and the amplification factor of the control tube V_1. E_r is the reference voltage. A_o is the gain of the voltage amplifier, $1/N$ is the voltage-divider attenuation, and R_L is the resistance of the load. If the output voltage changes an amount Δe_o, the portion of this change acting as signal voltage for V_2 will be $\Delta e_o/N$. With an amplification of A_o for V_2, the incremental voltage developed from grid to ground of V_1 will be $-A_o\ \Delta e_o/N$. Since the change in voltage from cathode to ground for V_1 is Δe_o, its grid-to-cathode signal voltage will be $-A_o\ \Delta e_o/N - \Delta e_o$. V_1 then acts like a resistance Rp_1 in series with an e.m.f. of $-\mu_1(A_o\ \Delta e_o/N + \Delta e_o)$. Neglecting the current through R_1R_2, the incremental current through V_1 and R_L is

$$\frac{e_1 - \mu_1(A_o\ \Delta e_o/N + \Delta e_o)}{Rp_1 + R_L},$$

which must equal $\Delta e_o/R_L$. Equating and rearranging yields the equation

$$\frac{\Delta e_o}{\Delta e_i} = \frac{1}{1 + \mu_1 + \frac{R_p}{R_L} + \frac{\mu_1 A_o}{N}} \tag{1}$$

where $\Delta e_o/\ \Delta e_i$ is defined as the input regulation. It is desired to minimize this quantity, which can be accomplished by increasing A_o.

The output regulation can be specified in terms of the equivalent source resistance R_i. Considering the regulator as an amplifier having negative voltage feedback, it can be shown[4] that the source resistance

$$R_i = \frac{R}{1 + AB} \tag{2}$$

where R is the output resistance of the amplifier in the absence of feedback, A is the amplifier voltage gain for the same condition, and B is the fraction of voltage fed back. In the circuit of Figure 2, V_1 can be considered as a cathode follower of output resistance[5] $\frac{Rp_1}{\mu_1 + 1}$ and voltage gain[6] $\frac{\mu_1 R_L}{Rp_1 + (1 + \mu_1) R_L}$. Substituting these values in equation (2) we get:

$$R_i = \frac{\frac{Rp_1}{\mu_1 + 1}}{1 + \frac{A_o}{N}\left(\frac{\mu_1 R_L}{Rp_1 + (1 + \mu_1) R_L}\right)}. \tag{3}$$

Since it is desirable to minimize R_i, a small ratio Rp_1/μ_1 is wanted. Because this ratio is the reciprocal of the transconductance, a tube of high transconductance should be used for V_1.

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4 H. F. Mayer, "Control of Amplifier Internal Impedance," _Proceedings of the Institute of Radio Engineers_, XXVII (March, 1939), 213.

5 Herbert J. Reich, _Theory and Applications of Electron Tubes_, p. 170.

6 _Ibid._, p. 168.

Considering equations (1) and (3) and component limitations, the main principles regarding the design of electronically regulated supplies may be summarized as follows:[7]

(1) High transconductance control tubes are desirable to reduce internal power losses and improve the regulation.

(2) A high-gain amplifier is required to obtain a maximum degree of regulation and low source resistance R_i.

(3) The unregulated rectified voltage e_i must always be great enough at the lowest encountered line voltage to supply the zero-bias drop in the series control tube at the highest combination of desired output voltage and current. This is the absolute limit of regulation, and for good results the supply voltage should actually exceed this requirement.

(4) Because any variation in the reference voltage will cause the output voltage to change, it is essential that this reference be as stable as possible.

(5) A suitable bleeder resistance is necessary to insure good regulation down to zero load current.

(6) Since the electronic circuits will fail to regulate at load currents in excess of a certain designed maximum, the peak current drawn must never exceed this maximum current rating. Hence, when it is desired to draw current in pulses of high peak

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7 Athony Abate, "Basic Theory and Design of Electronically Regulated Power Supply," <u>Electronics</u>, XXXIII (July, 1945), 481-482.

value but of reasonable average values, a large capacitor must be shunted across the supply output.

Sampling Circuit

The function of the sampling circuit, shown as A in Figure 1, is to provide a fraction of the regulator output or to provide some other voltage for comparison with the reference element in order to derive an error signal that may be used to operate the control element.[8]

The three broad classes of sampling networks are: linear networks, nonlinear networks, and compensating circuits. The linear type of sampling circuit shown in Figure 3 is a voltage divider made up of resistors. Wire wound resistors are usually used in order to get maximum stability. Potentiometers used in the circuit should be not larger than necessary for the required range of control so that the effect of the temperature coefficient of the potentiometer may be lessened.

Nonlinear networks merely use nonlinear components in a voltage divider circuit. Figure 4 shows an arrangement that is common when a nonlinear network is used. Nonlinear networks are of value because they have less d-c attenuation than linear networks.

Compensating networks used in degenerative regulators improve the regulation factor and decrease the output impedance. An example of compensating networks is seen in Figure 5. They are most practical in electronic regulators that have relatively low loop gain and are operated

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8 Greenwood, Holdam and Macrae, op. cit., XXI, 507.

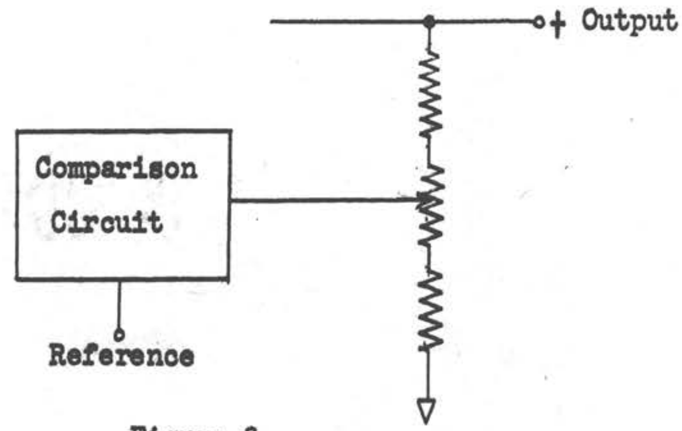

Figure 3
Linear Type Sampling Circuit

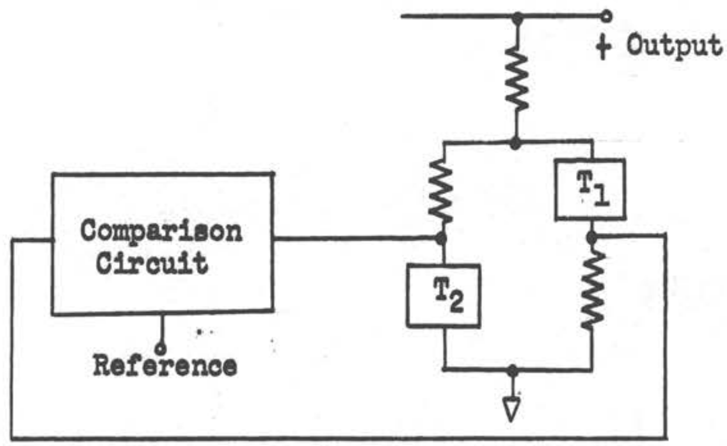

Figure 4
Nonlinear Element Sampling Circuit
(T_1 & T_2 are non-linear elements)

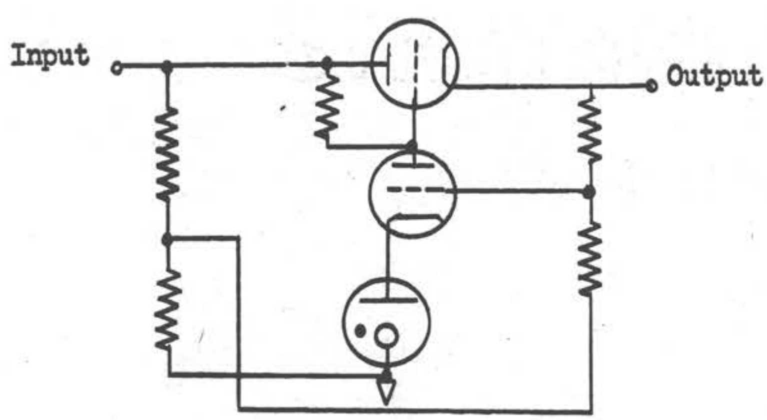

Figure 5
Compensating Type Sampling Circuits

over a limited range of line and load variations. The extent to which compensation can improve the operation of a regulator circuit is determined by the linearity of the sampling, comparison, amplifier, and control circuits.[9,10] The term "compensating circuit" is defined as a network introducing into the sampling circuit a voltage proportional to, or at least a direct function of, the input voltage and the load current in such a way as to increase the regulation factor or reduce the impedance of the source.

The main disadvantage of compensation methods are that circuit adjustment may be required when tubes are replaced. By observation of equations (1) and (3) it is seen that the higher the percentage of the output voltage fed back into the comparison circuit, the better the regulation. This fact must be taken into consideration in any type of network used as a sampling circuit if a high degree of regulation is to be obtained.

Many regulators employ more than one class of sampling circuit. Compensating circuits may be used in conjunction with linear networks to reduce the output impedance of the regulators. In general, linear networks have the best static stability.[11]

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9 W. R. Hill, Jr., "Analysis of Voltage-Regulator Operation," Proceedings of the Institute of Radio Engineers, XXXIII (January, 1945), 38-45.

10 F. V. Hunt and R. W. Hickman, "On Electronic Voltage Stabilizers," Review of Scientific Instruments, X (1939), 6.

11 Ibid.

References

Some of the most common elements now used as constant voltage references are dry batteries, standard cells, and gaseous voltage-regulator tubes. One of the newest developments in elements that may be used in the type of regulator presented in this thesis is the mercury oxide cell. The most important characteristic of a voltage reference is its constancy of voltage with aging, change of temperature, current drain, vibration, and change of position. The effect of momentary short circuits is another very important characteristic in the practical use of a reference element.

Dry Batteries

In laboratory equipment, dry batteries have been known to provide a voltage reference that is accurate to about 0.05 percent for a period of several months when operated under certain conditions.[12] This constancy for such a period is available only under conditions where there is not appreciable current drain from the battery. A battery will recover to a steady potential of somewhat lower value if short circuited briefly, but its life as a constant potential element is materially reduced.

Standard Cells

Standard cells are used extensively because of their precision constancy. The output of a standard cell is rated within $\pm$ 0.1 percent

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12 H. Sack, Constancy of EMF's of Dry Batteries, Cornell University (October, 1945).

of the original voltage over a temperature range of -16° to $+50^\circ$ C. The electromotive force of the standard cell changes very little with its temperature.[13] Standard cells must not be tilted more than 110° from upright position, and currents over 100 microamperes must not be drawn from them if a steady output voltage is to be maintained.[14]

Most of the standard cells in use, except those in standardizing laboratories which are called normal cells, are unsaturated cells whose e.m.f.'s are measured and certified as of a certain date. The unsaturated cell differs from the normal cell in that during manufacture the electrolyte is saturated at 4° C. and no excess of cadmium crystals is left in the solution.

The internal resistance of an unsaturated standard cell is usually within the range from 100 to 500 ohms. In the use of a standard cell, it is very important that very little current should ever flow in the cell and then for only short intervals. A current as small as one microampere passing through a cell for several minutes produces a measurable change in the e.m.f. After such a current flow has ceased, a few minutes are required for the cell to return to the original value. The current in a standard cell should never exceed 100 microamperes, and the period of use of current should always be kept as short as possible.

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13 W. Alpheus Smith, The Elements of Physics, p. 426.

14 Eppley Laboratory, Inc., "Eppley Standard Cells," Bulletin 1, (July, 1941).

If a standard cell is accidentally short circuited for a short time, it may recover to its normal e.m.f. in a month.[15] However, it should not be used as a standard again unless tests have shown that it is reliable.[16]

Gaseous Voltage-Regulator Tubes

Gaseous voltage-regulator tubes are extensively used as a means of obtaining a reference voltage in the degenerative type electronic voltage stabilizer. For purposes of analysis of the operation for a voltage-regulator tube, it is commonly considered to be the equivalent of a constant voltage in series with a linear resistance.[17,18] A report[19] made by George M. Kirkpatrick concerning the results of a number of tests on the most commonly used types of voltage-regulator tubes gives tabulated data showing that the tubes have a comparatively wide range of operating characteristics. Most voltage-regulator tubes have small spasmodic variations as large as 0.5 volt.[20]

From the tests on the V-R 105 made by Kirkpatrick, it was found that voltage jumps initiating spontaneously within the tube occur in large percentages of the V-R 105 tubes and at all current levels tested. These

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15 Frank A. Laws, Electrical Measurements, p. 309.

16 George V. Mueller, Introduction to Electrical Engineering, pp. 240-241.

17 Hunt and Hickman, loc. cit.

18 Hill, loc. cit.

19 George M. Kirkpatrick, "Characteristics of Certain Voltage-Regulator Tubes," Proceedings of the Institute of Radio Engineers, XXXV (May, 1947), 485-489.

20 Ibid.

voltage jumps were found to be as great as 0.2 percent of the operating voltage and occur in a random manner. The jumps were observed to occur simultaneously with sudden changes in cathode-glow area.

Kirkpatrick found that there were considerable variations of dynamic resistance and inductance values from tube to tube of the same type, particularly at low currents. Also, in the test made by Kirkpatrick, a number of readings of the tube voltage following firing were examined to determine the constancy of the operating voltage. Ten tubes of the three most common types of voltage-regulator tubes were fired five times each, and the readings of the tube voltage were taken after five minutes of operation. The average voltage and extremes as tabulated by Kirkpatrick may be seen in Table I.

Tube Type	Average Tube Voltage	Maximum Tube Voltage	Minimum Tube Voltage	Tube Current (Microampere)
V-R 75	71.90	72.59	71.13	5.5
V-R 105	106.68	108.53	102.83	20.0
V-R 150	151.25	152.95	149.40	20.0

Table I

Average, Maximum, and Minimum Tube Voltages (ten tubes) from Voltage-Regulator Tube Test Data[21]

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21 Kirkpatrick, loc. cit.

Mercury Oxide Cells

The mercury oxide cells were engineered and developed during the war following their invention by Samuel Ruben.[22] Their applications have grown immensely in electronic equipment.

The mercuric oxide cell is an alkaline dry cell.[23] Mercuric oxide is the depolarizer in a strongly alkaline solution of potassium hydroxide saturated with a zincate. The anode is zinc. These cells are known as "mercury cells," "Ruben cells," and "RM cells." The last designation is a contraction of the names Ruben[24] and Mallory, the inventor and a manufacturer.

Originally developed for use in portable military communications equipment, mercury oxide cells were required to operate in severe climatic conditions. The cells withstood high temperature and high humidity encountered in South Pacific jungles. Dependent on the conditions of the application, the mercury cells can provide as much as three or four times the energy-volume ratio of other kinds of batteries.

Commercially built mercury cells are tightly sealed, and since no deleterious side reactions normally occur, long shelf life is assured. Much longer than is possible with other kinds of cells, the long shelf life advantage of the mercury cells becomes even more pronounced under

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22 Samuel Ruben, U. S. Patents 2,422,045 and 2,422,046 (1947).

23 Maurice Friedman and Charles F. McCauley, "The Ruben Cell - A New Alkaline Dry Battery," Transactions of the Electrochemical Society, XCII (1947), 183-193.

24 Samuel Ruben, "Balanced Alkaline Dry Cells," Transactions of the Electrochemical Society, XCII (1947), 195-215.

storage conditions of high temperature and high humidity. Exposure to extremely low temperatures or long periods of cold storage has no adverse effect on battery life. The curve of Figure 6 shows results of storage life tests made in Mallory laboratories.[25] The diagram indicates that eighteen months after manufacture there is a service life reduction of only about seven percent.

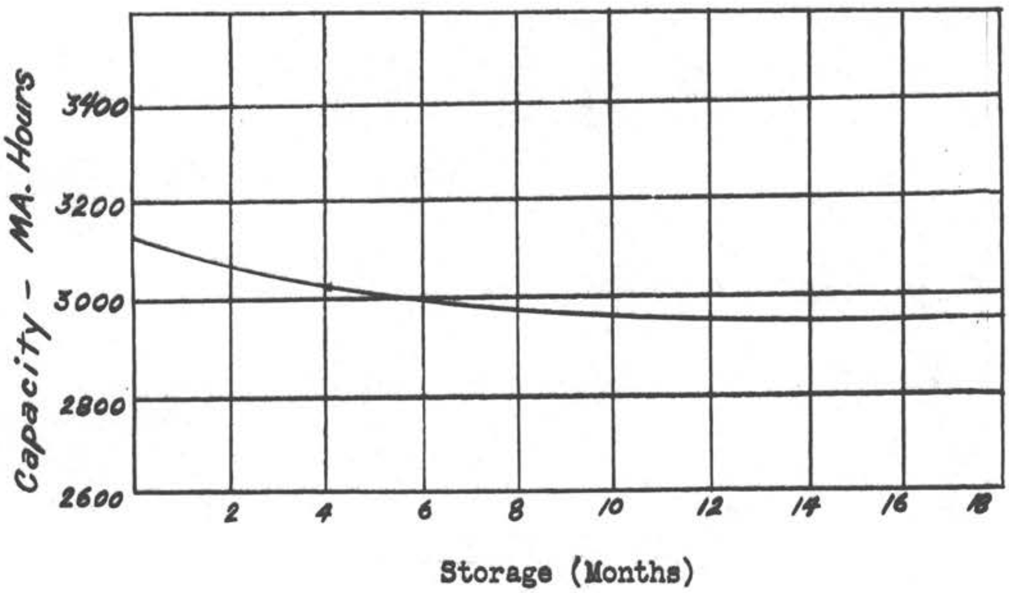

Figure 6

Effect of Storage on
Capacity of Mercury Cells

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25 P. R. Mallory and Company, Inc., "Mallory Mercury Batteries," Technical Information, Form No. SA-1-18-50-1M.

Mallory mercury cells remain dimensionally stable and are free from common battery leakage problems. The cells do not leak even at high temperatures or after they are entirely exhausted. Mercury cells of the type made by Mallory do not need rest periods in order to provide all of their electro-chemical energy. Within design load limits, the ampere-hour service life of the cells is the same under either continuous or intermittent loads. Only at very heavy loads, beyond the normal design loads of the cells, intermittent operation may improve the battery service life. Under these very heavy drain conditions, rest periods aid in the dissipation of polarization products resulting from the abnormal current drains.

Because of their extremely constant no-load voltage, mercury oxide cells provide a battery characteristic which is unattainable except for standard cells. Virtually unaffected by time and temperature, the no-load potential of the RM type mercury cells, after equilibrium is reached, is 1.345 $\pm$ 0.005 volts with a temperature coefficient comparable with that of standard cells.

Figure 7 shows discharge curves at light drains of 0.5 milliampere, one milliampere, and two milliamperes. At a one milliampere current drain, the voltage regulation of a 3RF Mallory mercury cell is less than one percent for 1,000 hours of continuous discharge.[26] However, under no-load operation, the regulation of the mercury cells is as good as the voltage regulation of the standard cells. Ruben reported the internal

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26 Mallory, loc. cit.

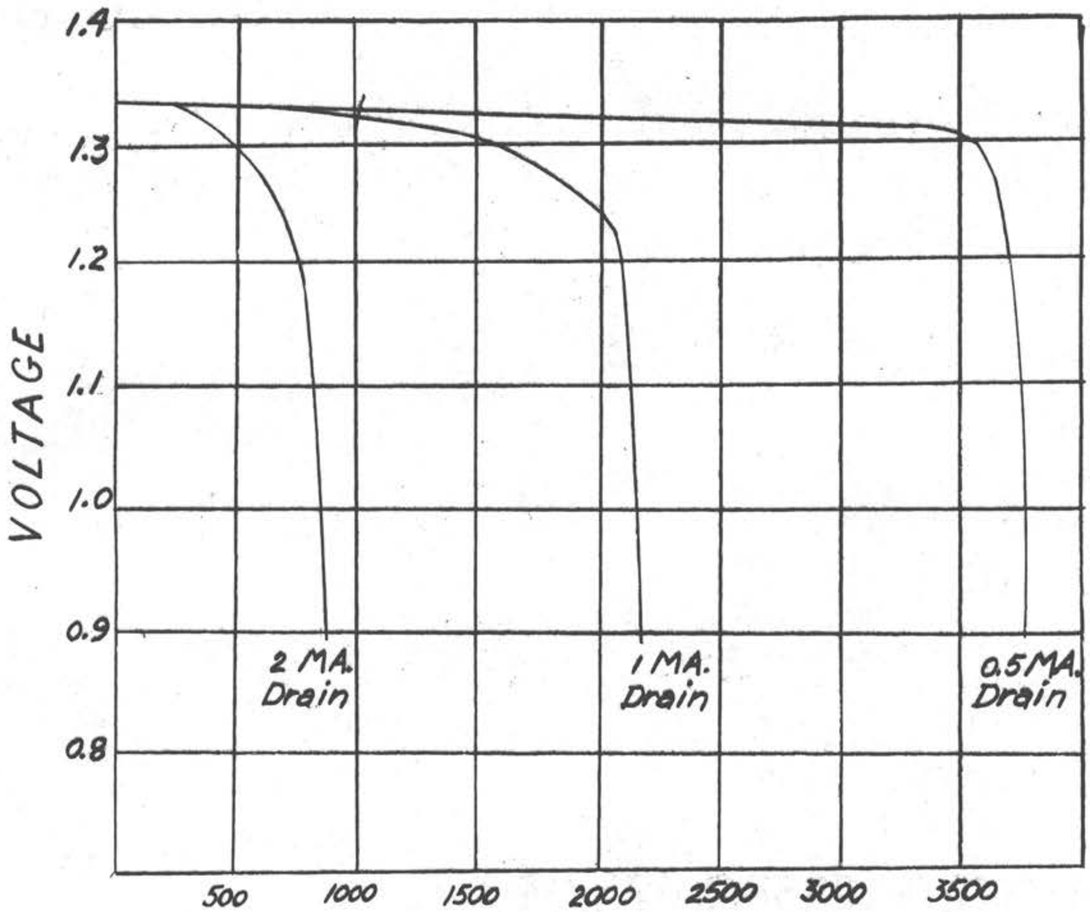

Figure 7

Light Drain Characteristics of Type 3RF Mercury Cells[27]

resistance of the button and cylindrical types of mercury cell to be 0.42 and 0.22 ohm, respectively, by an a-c method of measurement at 1,000 cycles per second.[28]

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27 Ibid., p. 3.

28 Ruben, loc. cit.

Another desirable characteristic of the Mallory mercury cell is its ability to resist conditions of high humidity, salt air and spray, and corrosive fumes. These cells are also completely unaffected by pressures ranging from a high vacuum to thousands of pounds per square inch. Tested at acceleration values as high as 120 gravities and subjected to severe impact shocks, the RM type Mallory mercury cell was found to be completely unaffected.[29]

Conventional zinc-carbon type batteries are constructed with a drawn zinc can which serves as both the anode and the cell container. Mallory mercury cell anodes also are of zinc but in a much different, purer form. Two types of anodes are used: (1) a pellet pressed of very pure zinc powder of uniform grain size, and (2) a roll of uniformly thin, corrugated zinc strip. The depolarizing cathode consists of chemically pure mercuric oxide to which a small amount of graphite is added. All Mallory mercury cells contain substantially the same type of electrolyte, a concentrated aqueous solution of potassium hydroxide and zinc oxide. Until electrical energy is drawn from the mercury cells, there is no internal cell reaction because stable chemical components and passive cell case materials are used. Initially the no-load terminal voltage is 1.345 volts, dropping only slightly at moderate loads until the end of its useful life is reached. Simultaneous with the production of energy, an electro-chemical reaction occurs at both the anode and depolarizing cathode active surfaces. Figure 8 shows the basic construction and chemical components of the button type

29 Mallory, loc. cit.

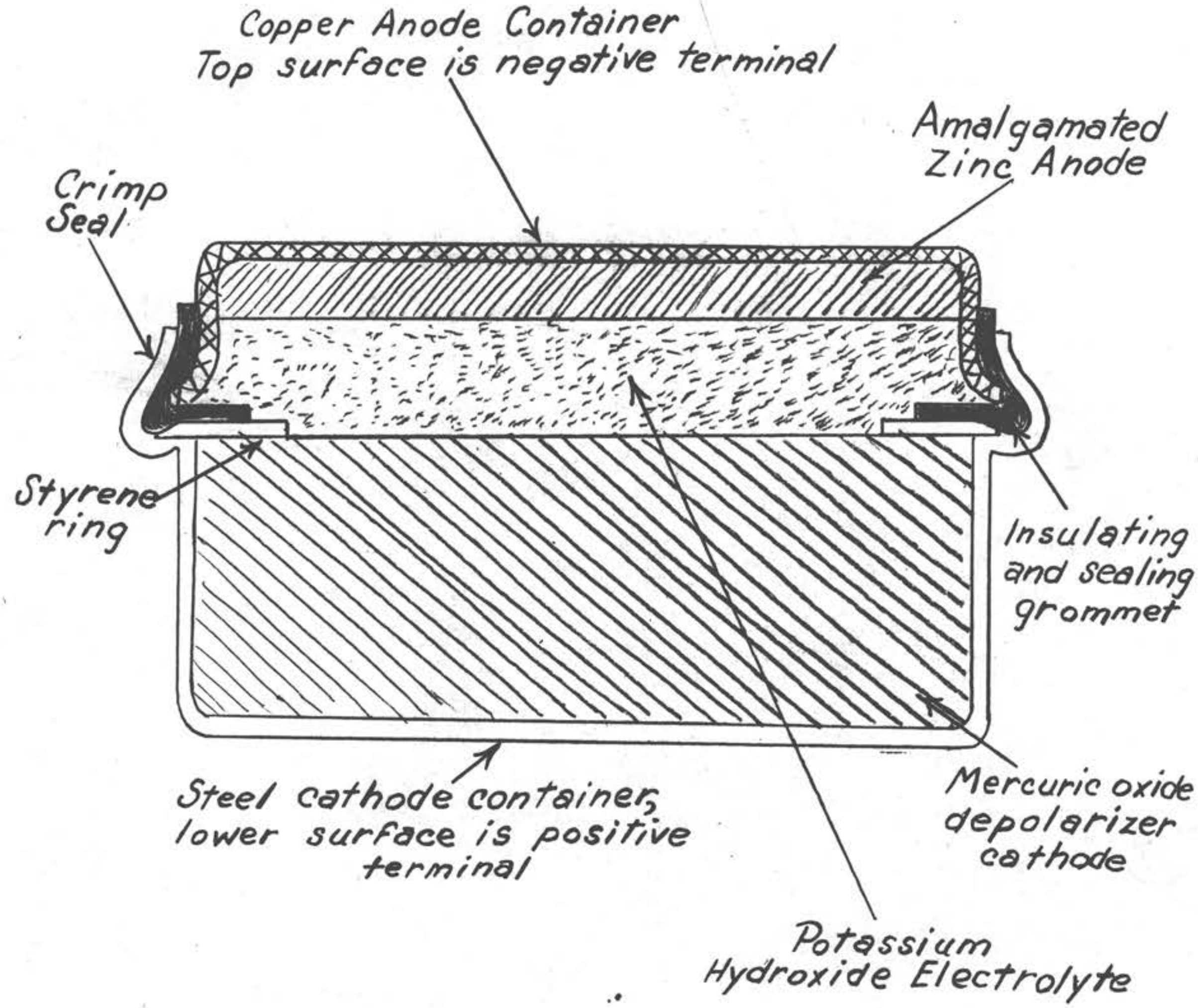

Figure 8

Cross Sectional View of Button Type Mercuric Oxide Cell[30]

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30 Ibid.

mercury oxide cell. At the end of useful service life, commercial RM cells are designed so that the zinc anode is entirely oxidized before the mercuric oxide cathode is completely reduced. Should these commercial cells be left connected at the end of their useful life, no further reaction of any type occurs within the cell.

The mercury oxide cells have a precalculated relationship between the amount of active components and the amount of available energy. When current drains of 100 milliamperes per square inch of electrode surfaces are not exceeded, a minimum value of 200 milliampere-hours is delivered for each gram of depolarizing material or for about 1.16 grams of active cell components, including cathode depolarizer, anode, and electrolyte material. Although the cell will operate at much higher current drains, some sacrifice in operating efficiency must be expected.

Mallory mercury cells have further desirable characteristics in that their construction is mechanically rugged. The containers of the cells are nickel-plated in order to resist external corrosion and to attain greatest passivity to internal cell components. The cell top which is made from a metal that does not react chemically with the action in the cell system makes possible the use of a carefully measured quantity of zinc and a slightly excess quantity of mercuric oxide. This special combination prevents evolution of hydrogen gas at the end of the useful service life.

As an example of the ruggedness of construction, the button type cell may be used. The container for each cell is a shallow steel nickel-plated cylinder, closed at the bottom and open at the top. In the button cell shown in Figure 8, only the lower half of the container is steel.

The type of materials and their arrangement in the mercury oxide cell enables it to be mounted in any position without affecting its characteristics.

Comparison Circuits

The comparison circuit in a degenerative regulator produces a signal that is a measure of the magnitude and sense of the difference in potential between the sampling circuit and the reference element.[31] There are two broad classes of comparing circuits that have been generally used in electronic regulators. These two common comparing circuits are direct-coupled amplifiers and modulators. A new method of performing the comparison-circuit action, which is used in the new type electronic regulator system presented in this thesis, is a combination of a synchronous commutator and a high gain a-c voltage amplifier circuit. A discussion of each type of comparing circuit separately is necessary in order to clearly present their characteristics.

Direct-Coupled Amplifiers

Direct-coupled amplifiers are used as comparison circuits in regulators where a high degree of regulation is not required of the source. The three principal types of direct-coupled amplifier circuits used in regulators as comparison circuits are the single-ended amplifier, the cascode amplifier, and the balanced amplifier.

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31 Greenwood, Holdam and Macrae, *op. cit.*, p. 511.

The single-ended amplifier usually employs a multigrid tube as seen in Figure 9, in order to provide high gain, which is necessary for high regulation as seen in equation (3).

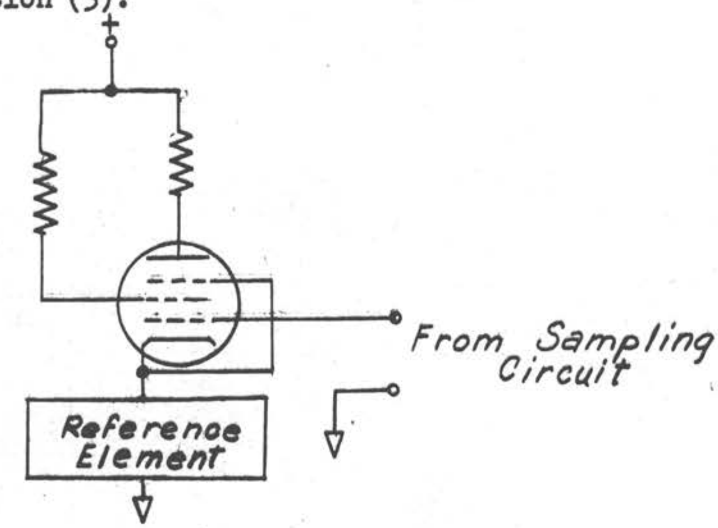

Figure 9
Single-ended Direct-coupled Amplifier
Comparison Circuit

The cascode amplifier seen in Figure 10 has the advantage over the single-ended amplifier in that it has higher gain. The increased gain reduces the effective output impedance and hence improves the regulation.

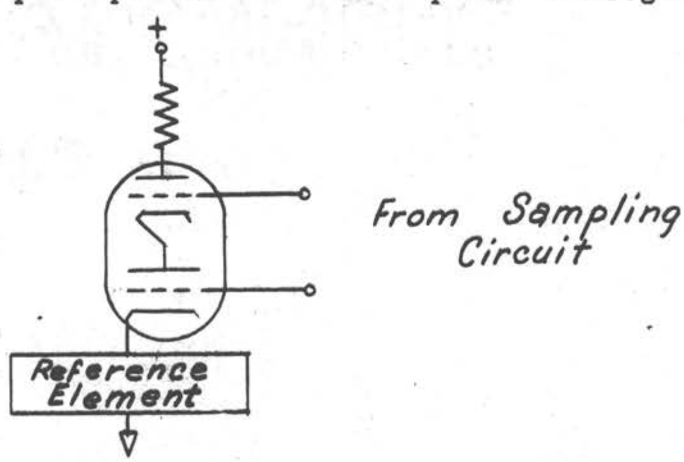

Figure 10
Cascode Direct-coupled Amplifier
Comparison Circuit

An example of a balanced direct-coupled amplifier is seen in Figure 11. This circuit has advantage over the single-ended and cascode direct-coupled amplifier in that it loads neither the reference element nor the sampling circuit.

The principal disadvantage of any type of direct-coupled amplifier is that the amplifiers have a tendency to drift; i.e., a change in potential anywhere in the circuit will cause the currents and potentials of all succeeding tubes to vary.[32] Heater voltage fluctuations and aging cause small changes in cathode-grid voltage. These fluctuating effects have about the same magnitude for diodes, triodes, tetrodes, and pentodes; for high and low μ's; and for high and low transconductances. In fact, these effects appear to be common to all oxide-coated unipotential cathode structures.[33]

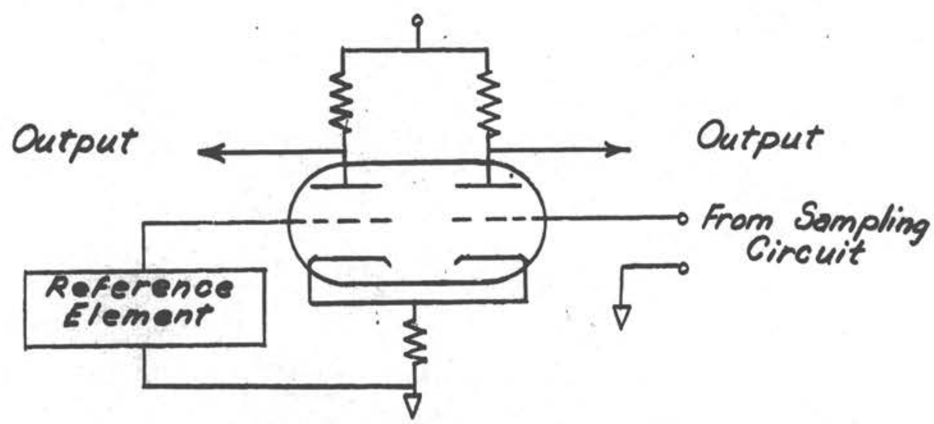

Figure 11
Balanced Direct-coupled Amplifier
Comparison Circuit

32 Austin V. Eastman, <u>Fundamentals of Vacuum Tubes</u>, p. 285.

33 Greenwood, Holdam and Macrae, <u>op. cit.</u>, p. 513.

Modulator Comparison Circuits

The modulator comparison circuits utilize the high, stable gain of a-c amplifiers by changing the error voltage to an alternating voltage. This a-c voltage is then amplified by the a-c amplifiers, detected and changed to a d-c voltage that is much larger than the original error voltage.

There are two basic classes of modulators that have been used in comparison circuits in electronic regulators. The two types are vacuum-tube modulators, and mechanical-switch modulators.

An example of one type of vacuum-tube modulator is seen in Figure 12. Modulators of this type utilize an external a-c voltage as a carrier which is varied in magnitude at the output proportionally to the value of the voltage difference between the reference and sampling-circuit voltage. Tube modulators have essentially the same limitations of stability as have d-c amplifiers, because nearly all instability is due to the characteristics of the oxide-coated cathode.

Mechanical-switch modulators used as comparison circuits provide a much higher order of stability than electronic tubes. Accuracies of one millivolt are usually realized with switch-type modulators. Figure 13 shows a mechanical-switch modulator comparison circuit that has been used in precision d-c voltage supplies.[34] The circuit utilizes a phase detector to change the a-c voltage to a relative d-c voltage that may be applied to the control tube.

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34 Ibid., p. 553.

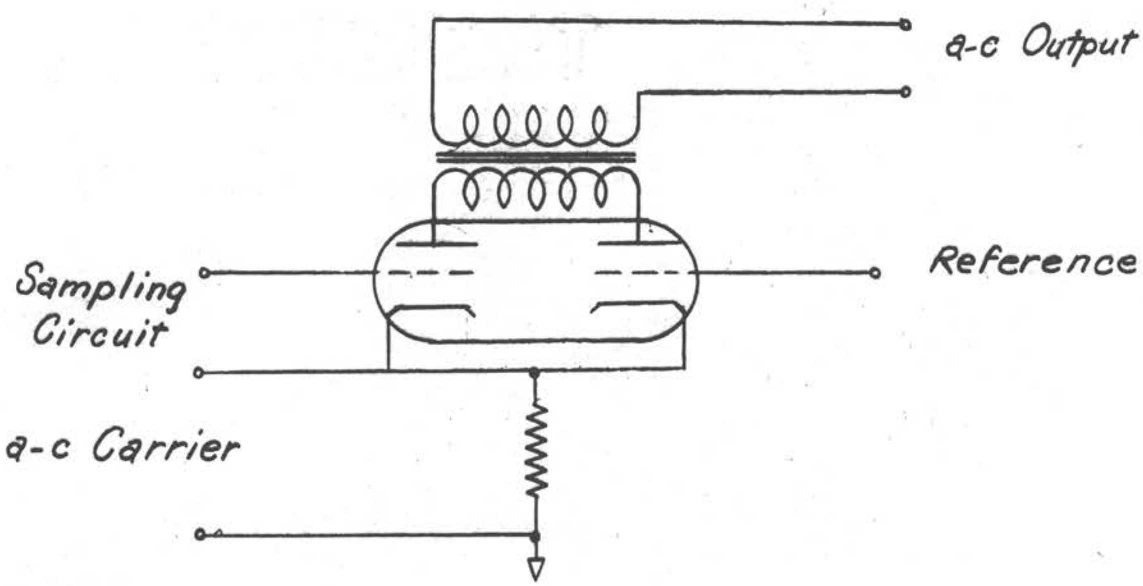

Figure 12
Vacuum-Tube Modulator
Comparison Circuit

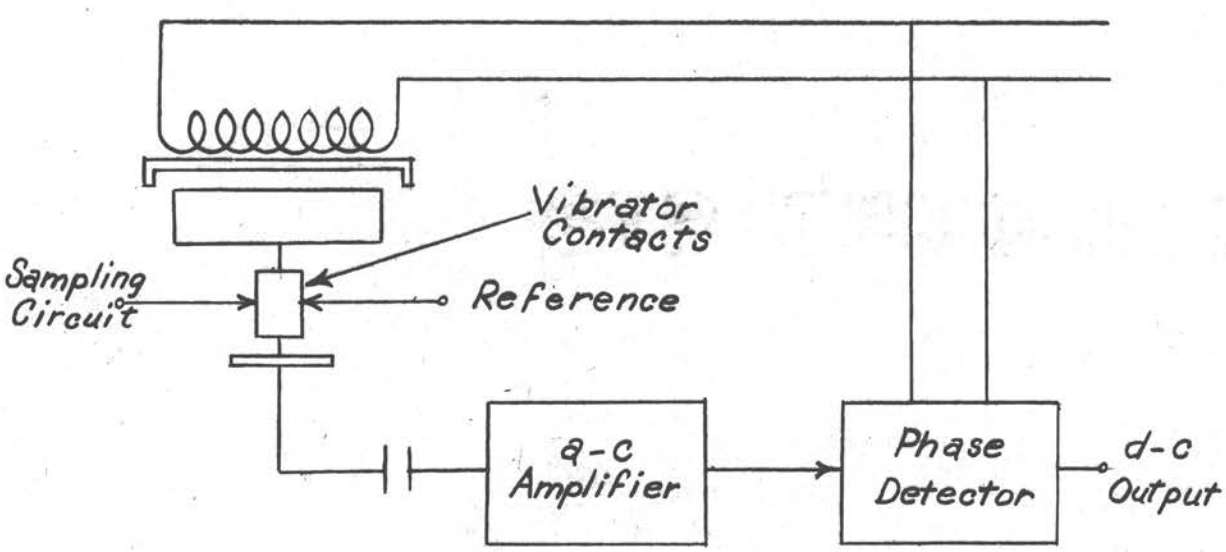

Figure 13
Switch-Type Modulator
Comparison Circuit

Figure 14 shows a new type of modulator mechanical-switching comparison circuit, which is one of the unique features of the regulator system presented in this thesis. This circuit utilizes a switching device for both modulator and detector action and has the stability of both mechanical switching and a-c amplifiers without an elaborate phase detector circuit as is used in the method of Figure 13.

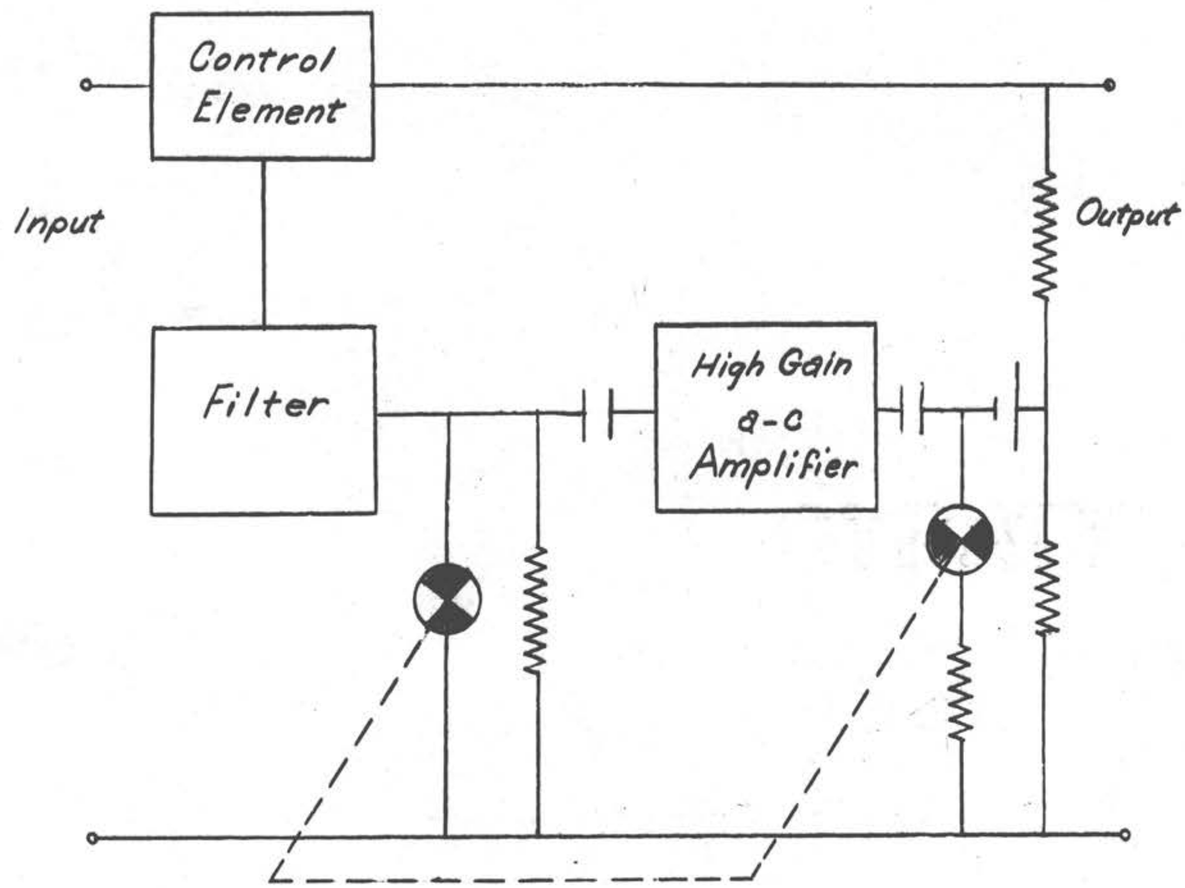

Figure 14
New Type Mechanical Switch Modulator
Comparison Circuit

The synchronous converter used in the circuit described in the next chapter is a relatively newly developed Western Electric type 276 mercury-contact relay. The electrical arrangement of the relay is seen in Figure 15.

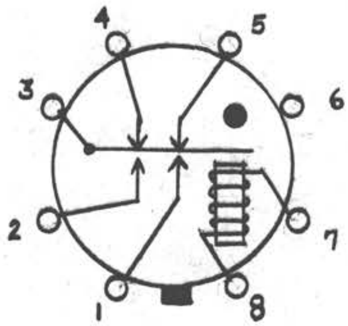

Figure 15
Base Connection View of the
Western Electric 276 Type
Mercury Contact Relay

Series Control Elements

The control element of a degenerative regulator modifies the input in order to obtain the desired output. Since vacuum tubes have fair linearity and very short time constants they are used to regulate d-c supplies.

The choice of the series control tube or tubes will depend on the amount of current that the power source will have to supply.[35] Generally, a power-amplifier tube is used because it will allow greater plate

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35 M. S. Kay, "Electronically-Regulated Power Supplies," Radio News, XXXII (November, 1944), 40-42.

dissipation and current flow than ordinary amplifier tubes. If one tube should prove insufficient then several may be placed in parallel. Experimentally, the amount of wattage being dissipated in the tube may be determined by connecting it into the circuit and measuring the voltage dropped across it. This figure multiplied by the current through the tube gives the wattage in the tube. This calculation must be made since plate dissipation rather than current or voltage is the limiting factor for power tubes.

By observation of equation (3), it can be seen that high transconductance tubes are necessary in the control element in order to have high regulation. Popular control tubes for direct-current regulators include the 6V6, 6L6, 6B4, 6AS7, and a recently developed miniature power tube, the 6AQ5.

Characteristics of control tubes that are less important than plate dissipation but in some cases must be considered in the design of a voltage regulator are heater power loss, allowable heater-cathode potential, and the desirability of keeping the number of separate tube types as low as practical in a particular instrument.

CHAPTER III

REGULATOR CIRCUIT DESCRIPTION AND CHARACTERISTICS

Figure 16 and Figure 17 show the top view and the bottom view of an experimental model of the regulator system presented in this thesis. The circuit diagram is shown in Figure 18. This circuit was designed for a steady voltage of approximately 40 volts but with the adjustments that are available the range may be varied from 35 to 50 volts without affecting the regulation characteristics appreciably. The input to the regulator network of the experimental model is an unregulated d-c voltage that is adjustable from approximately 200 to 400 volts.

The sampling circuit of the regulator is of the linear type consisting of the combination of R_1 and R_2. These resistors constitute a nominal 40:1 voltage divider with R_2 being adjustable so that the voltage across it may be made exactly equal to the reference voltage when the regulator output is at the desired value. The reference cell represented by E_r in Figure 18 is actually a Mallory Mercury RM3 cell.

The comparison circuit is a combination of a synchronous converter and a high gain a-c amplifier. One half of the action of the synchronous converter changes any variation of the voltage across R_2 with respect to the reference into an a-c voltage, the phase of which depends on the direction of variation of the output voltage. The synchronous converter used in the circuit of the experimental model is a Western Electric mercury-contact relay with a 60-cycles-per-second rate of vibration. This type of converter was used because the mercury wetting action minimizes the development of contact potential. The other half of the action of the

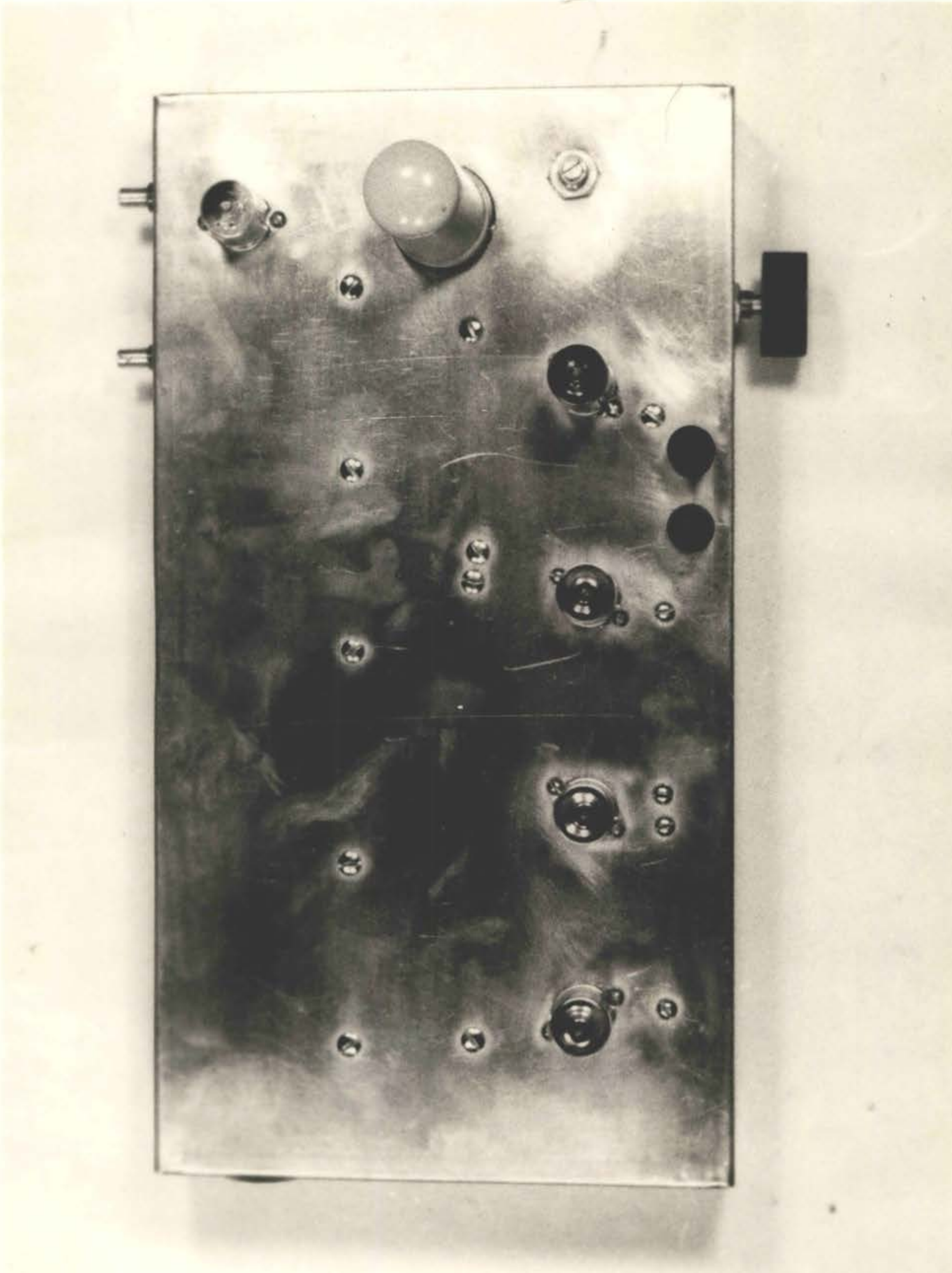

Figure 16
Top View of Experimental Model

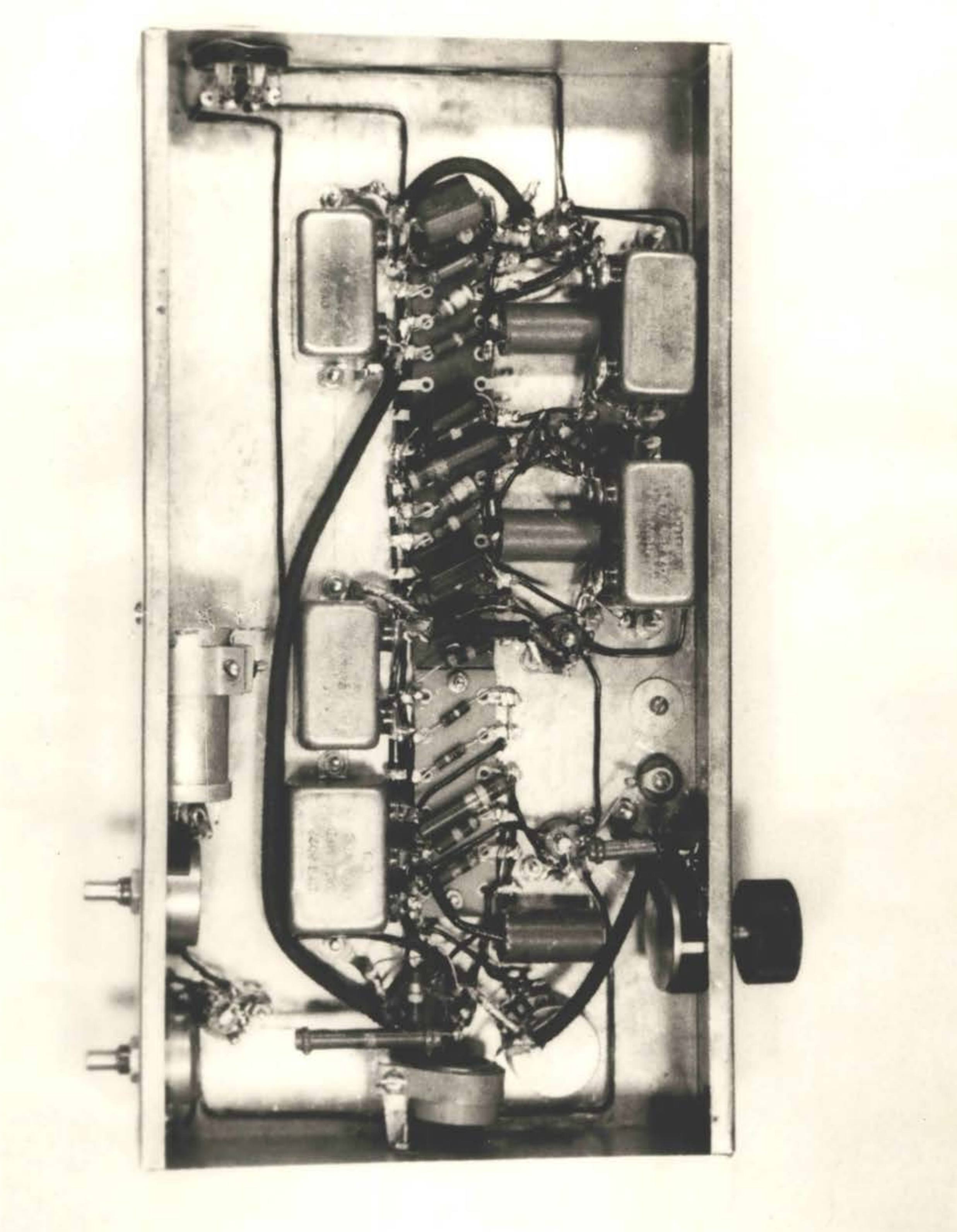

Figure 17
Bottom View of Experimental Model

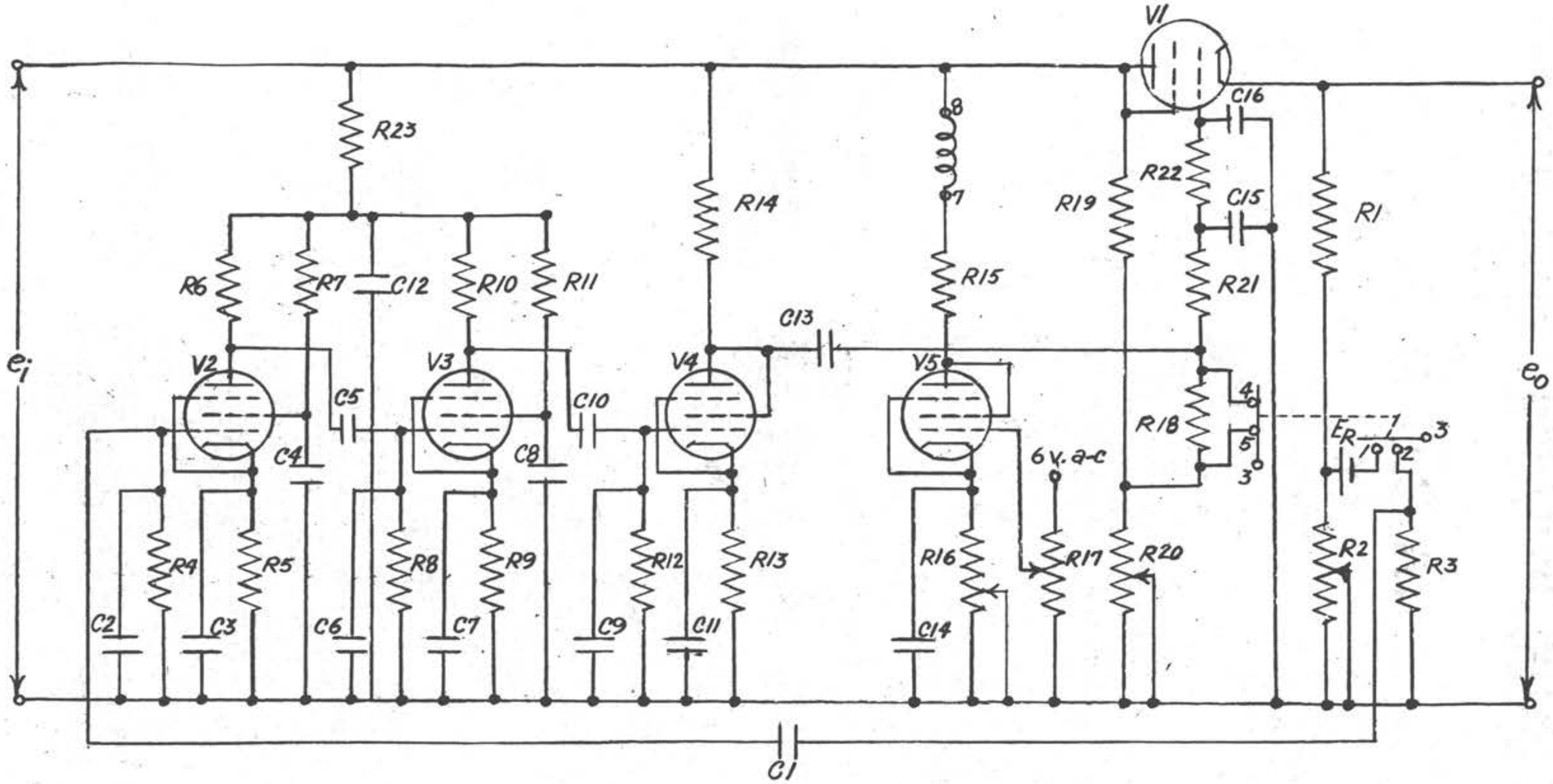

Figure 18

Circuit Diagram of Experimental Model

(Contacts 1-8 are relay contacts seen in Figure 15)

TABLE II

LIST OF PARTS

Resistors (All resistances are in ohms. K represents 1000; meg. represents megohms.)

R1	20 K	R13	5 K
R2	1 K potentiometer	R14	50 K
R3	100 K	R15	12 K
R4	500 K	R16	25 K potentiometer
R5	2 K	R17	100 K potentiometer
R6	250 K	R18	50 K
R7	1 meg.	R19	100 K
R8	500 K	R20	100 K potentiometer
R9	3 K	R21	1 meg.
R10	250 K	R22	1 meg.
R11	1 meg.	R23	50 K
R12	500 K		

Capacitors (All capacitances are in microfarads.)

C1	0.1	C10	0.1
C2	0.0015	C11	4, 600 v. electrolytic
C3	4, 600 v. electrolytic	C12	0.5
C4	0.5	C13	4, 600 v. electrolytic
C5	0.1	C14	0.5
C6	0.0015	C15	20, 600 v. electrolytic
C7	4, 600 v. electrolytic	C16	0.25
C8	0.5	C17	0.25
C9	0.0015		

Tubes

V1	6AQ5
V2	6AK5
V3	6AK5
V4	6AK5
V5	6AK5

Relay

Western Electric Type 276 mercury-contact relay converter serves as a synchronous half-wave rectifier for the output of the a-c amplifier.

The a-c amplifier section consists of the circuits of V2, V3, and V4. The first two stages consisting of V2 and V3 are high-gain pentode stages using type 6AK5 miniature vacuum tubes. The third stage of amplification, consisting of a 6AK5 connected as a triode, is designed to enable the amplifier section to handle a relatively high voltage swing. The design of the high-gain amplifier section used in the comparison circuit was greatly complicated by the many possibilities of regeneration. Regeneration, in general, is caused in a high-gain amplifier circuit by the transferring of energy from the output to the input of the amplifier.[1] Not only the choice of electrical components but also the physical layout of the components was very critical.

By experimentation, it was found that every precaution was necessary to prevent regeneration in the amplifier section consisting of V2, V3, and V4. The possibility of high-frequency oscillation was reduced by decreasing the high-frequency response of the amplifier, and by reducing the possibility of regeneration due to unwanted capacitive coupling.

The high frequency response of the amplifier was reduced by placing the capacitors C2, C6, and C9 across the grid resistors R4, R8, and R12 respectively. The capacitors have such a value that any high-frequency voltage that occurs on the grid is reduced greatly in amplitude

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1 Eastman, op. cit., p. 337.

without affecting appreciably the low-frequency response of the amplifier. To reduce the possibility of regeneration due to unwanted capacitive coupling, special attention was given to the lead lengths and the placing of the circuit components to obtain as much shielding between stages as possible. The amplifier tubes V2, V3, and V4 were so arranged that leads could be made as short as the size of the components would allow. Shielded leads were used for connections where the components were relatively far apart. By experimentation it was found that a fair amount of shielding between tubes could be accomplished by placing the electrolytic cathode by-pass capacitors C3, C7, and C11 physically between the tube sockets of the amplifier stages. The physical layout can be seen in Figure 17.

Because low-frequency regeneration, or "motorboating," is caused by impedances common to both the input and the output circuits of the amplifier, the output impedance of the unregulated power source presented a problem in the design procedure. To reduce the possibility of regeneration caused by this common impedance, a resistance-capacitance decoupling filter[2] was used in the B+ circuit. The filter consists of R23 and C12 with the resistance of R23 much larger than the reactance of C12 at the lowest frequency for which motorboating appeared.

The control section of the regulator circuit consists of the tube V1. The bias for the control tube is obtained by the divider circuit consisting of R19 and R20 and is connected to the grid of the series tube through R18, R21, and R22. The regulation effect is accomplished by changing the

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2 <u>Ibid.</u>, p. 339.

bias of the control tube in a direction that tends to correct for any change of output voltage whether due to a change in either input voltage or output current. The change in bias is accomplished by developing across R18 an amplified and rectified voltage from the comparison circuit. This voltage is filtered by the combination of R21, R22, C15, and C16, giving a change in d-c bias proportional to phase and amplitude of the error signal.

In order to explain the circuit action of the regulator, a change in the output may be assumed and the resultant signal followed through the different stages until regulation is obtained. Under static conditions with the desired voltage at the output, the voltage drop across R2 is adjusted to be just equal to the reference voltage, so that no a-c voltage is fed into the amplifier section. Assuming a decrease in output voltage, which may be due to either an increase in load current or a decrease in input voltage, the potential drop across R2 is decreased. The action of the chopper impresses a pulsating square wave 60-cycles-per-second voltage across R3 with an amplitude equal to the difference between the voltage across R2 and the reference voltage. When the output tends to decrease, the amplitude of the square-wave voltage across R3 is negative with respect to ground. The a-c error voltage is coupled to the input of the high-gain amplifier by the combination of C1 and the grid resistor R4. Due to the action of the coupling capacitor C1 the average value of the error signal is shifted in such a way as to give equal amplitudes to the positive and negative half cycles of the signal voltage applied to V2. The effective phase shift through the three stages of amplification is 180°. Since the chopper contacts across R18 are open when the contacts at the input to the amplifier are closed, it can be seen that the positive half of the greatly amplified a-c error voltage is developed across R18 and the negative portion is shunted by the second part of the converter action. The positive half of the amplified error signal is filtered to a positive d-c bias voltage for the control grid of V1 by the filter network consisting of R21, C15, R22, and C16. The increase in positive voltage on the grid caused by the amplified error voltage increases the conduction of V1 and decreases the voltage drop across it. The change in drop across V1 corrects for the attempted drop at the output terminals. A similar analysis may be made by assuming an attempted increase in voltage at the output terminals.

The 60-cycles-per-second energizing current for the coil of the chopper is obtained by the circuit of the tube V5. The correct value of d-c current with a-c voltage impressed on it is obtained by the adjustment of R16 and R17. The adjustments must both be made in order to get the proper values of both the d-c and the a-c components in the coil so that the time that the vibrator is at each pair of contacts is equal and stable.

The tube used as the control element in the experimental model described is the 6AQ5 type with a maximum current rating as connected in the circuit of approximately 50 milliamperes. Power sources with the ability to supply more current may be designed by using a control tube of higher power dissipation.

The characteristics of the experimental model were measured by the use of the combination of a Leeds and Northrup type K potentiometer and a Leeds and Northrup suspension galvanometer. The data taken during the test are recorded in Table III.

The variation characteristic of the output of the regulator circuit with a changing input voltage may be seen in the curve of Figure 19. From the curve it is seen that as the input voltage is varied from a value of 240 volts up to 340 volts, the variation of output voltage is approximately 0.067 volt, which represents a regulation of approximately 0.17 percent. This is very good regulation considering that at the extremeties of the input voltage variation, the action of the converter is affected.

The regulation with constant input voltage and variable output current is shown in Figure 20. Considering the variation of load current from zero to 40 milliamperes, it is seen that the variation in output voltage is 0.048 volt which is equivalent to a regulation of approximately 0.12 percent.

Figure 21 shows the characteristic of the regulator circuit with varying load while not holding the input voltage constant. With a variation of load current of zero to 40 milliamperes the output voltage varies 0.150 volts. This variation is extremely low considering that the d-c input source has very poor regulation. For example, in the experiment made to obtain the curve of Figure 21 the input voltage to the regulator varied from 300 to 255 volts over the load current variation of zero to 40 millamperes.

TABLE III

DATA SHEET

Run 1 - Input voltage varied with constant load current.

Unregulated Input e_i Volts	Load Current I_L Milliamperes	Regulated Output e_o Volts
340	25	38.795
320	25	38.772
300	25	38.767
280	25	38.743
260	25	38.734
240	25	38.728

Run 2 - Variation of load current with constant input voltage.

Unregulated Input e_i Volts	Load Current I_L Milliamperes	Regulated Output e_o Volts
290	0	38.814
290	10	38.810
290	20	38.807
290	30	38.775
290	40	38.766

Run 3 - Variation of load current with input voltage unregulated.

Unregulated Input e_i Volts	Load Current I_L Milliamperes	Regulated Output e_o Volts
300	0	38.820
295	10	38.825
285	20	38.773
265	30	38.737
255	40	38.670

TABLE IV

TEST EQUIPMENT

(1) Weston Standard Cell, Model 4, No. 8901.

(2) Volt Box, Leeds and Northrup Co., Ser. No. 10910.

(3) Milliammeter, Jackson, Model 665-J-2.

(4) Volt Ohmyst Junior, Model 165-A, Ser. No. 24821.

(5) Volt Ohmyst Junior, Model 165-A, Ser. No. 24623.

(6) Potentiometer, Leeds and Northrup Co., Ser. No. 398826, Type K.

(7) Leeds and Northrup Suspension Galvanometer, Ser. No. 155501.

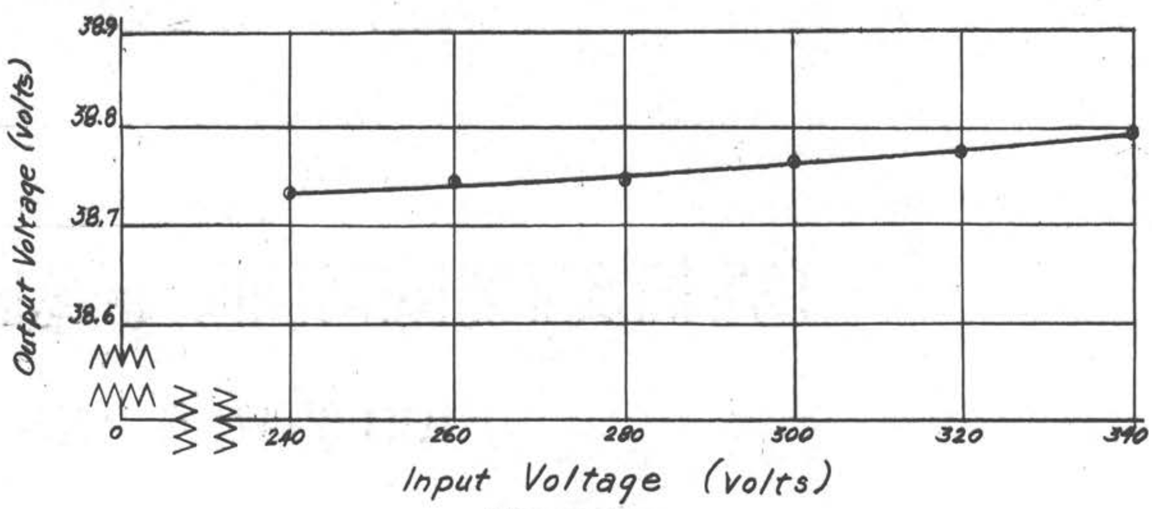

Figure 19
Regulation Characteristic of
Experimental Model with Varying
Input Voltage at Constant Output Current
(I_L = 25 Milliamperes)

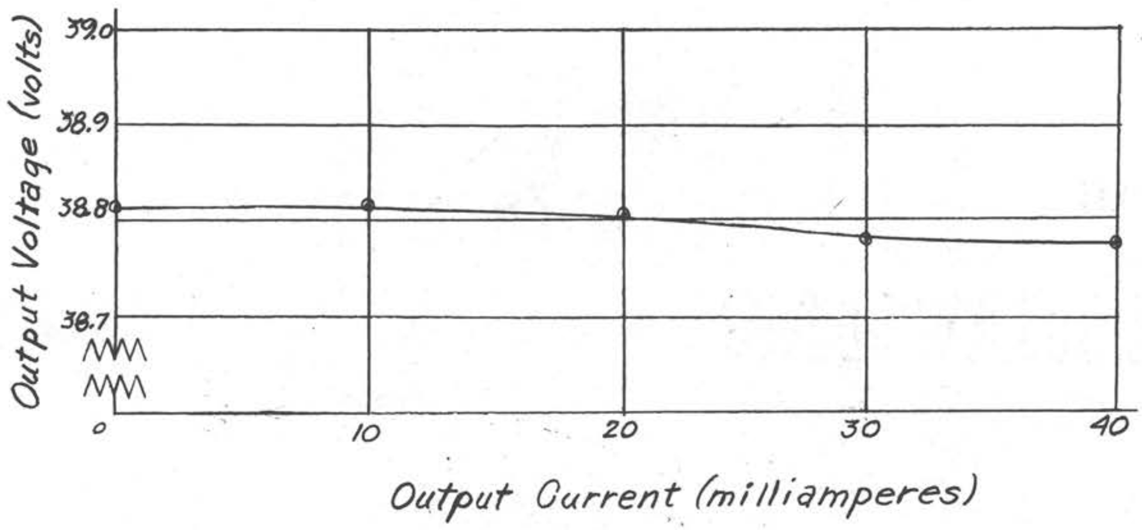

Figure 20
Regulation Characteristic of
Experimental Model with Varying Output
Current at Constant Input Voltage
(e_i = 290 volts)

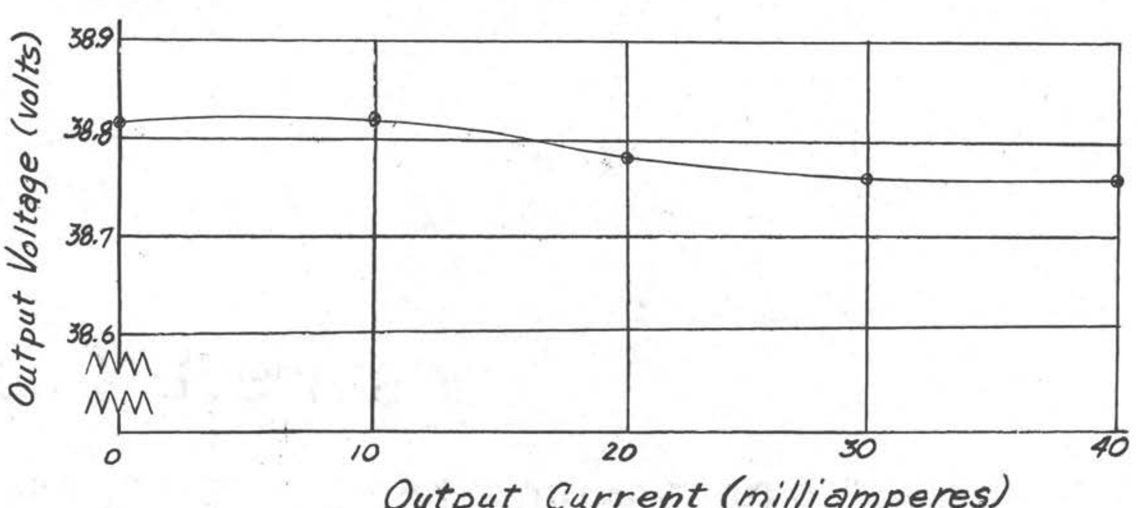

Figure 21
Regulation Characteristic of
Experimental Model with Varying Output
Current and Unregulated Input Voltage

CHAPTER IV

SUMMARY AND CONCLUSION

The advantages of the new system of obtaining a precision regulated voltage have been presented by comparing its components with the components used in common regulated power supplies and by explaining the circuit action and recording the operating characteristics of an experimental model. The new system has the advantages of a linear sampling circuit, an extremely stable and rugged voltage reference in the form of the Mallory mercury cell, the stability and very high gain that is available in the a-c amplifier, and the accuracy and stability of the mechanical switching synchronous converter, the Western Electric mercury-contact relay.

The regulation of the experimental model was found to be approximately 0.15 percent. Although this degree of regulation is probably much greater than is necessary for ordinary electronic apparatus, many electronic instruments require a power source in this range of stability. The regulation of the experimental model is considerably greater than that of the ordinary commercial regulated power supplies and has the advantage of a relatively simple circuit. The cost of the synchronous converter may economically restrict the use of this system in many applications.

It is believed that by a more careful adjustment of R2, which is a very tedious adjustment, the circuit shown in Figure 18 can be made to have a higher degree of stability. The circuit of the experimental model can be altered to perfect a source of as high a degree of regulation as may be desired. This may be accomplished by increasing the feedback amplification of the error signal and careful adjustment of R2 in the sampling circuit. However, the problem of preventing regeneration is greatly increased as the feedback amplification is made greater.

Although the circuit shown in Figure 18 does not have as high a degree of regulation as may be achieved by the use of the new system using the Mallory mercury cell, the a-c amplifier, and the Western Electric mercury contact relay, the experimental model does prove the practicability of this system of obtaining voltage regulation. This circuit can, of course, be readily modified to produce greater current handling ability, a different output voltage, or a higher degree of regulation if desired.

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